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DELINEATION OF EMERGENCY SURFACE  
DECOMPRESSION AND TREATMENT PROCEDURES  
FOR  
PROJECT TEKTITE AQUANAUTS

**CASE FILE**  
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FOR  
PROJECT TEKTITE AQUANAUTS

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DELINEATION OF EMERGENCY SURFACE DECOMPRESSION  
AND  
TREATMENT PROCEDURES FOR PROJECT TEKTITE AQUANAUTS

*Peter O. Edel*

ABSTRACT

Project Tektite will require that four scientist-aquanauts live for two months in a habitat at a depth of 42 FSW in Lameshur Bay, St. John, Virgin Islands, during which time their breathing mixture will be 91% N<sub>2</sub>-9% O<sub>2</sub>. A series of experiments was therefore conducted to determine to what degree of safety the scientists can make a "no-decompression" ascent to surface from the habitat, and the maximum surface decompression interval they can safely undergo.

From these experiments, it was determined that a 15-minute surface interval was safe for six subjects, whereas one subject developed serious neurocirculatory symptoms after 19 minutes on the surface.

Recompression-decompression schedules were calculated for treatment of these subjects after their exposure to surface intervals of various lengths of time. All subjects were successfully treated according to these tables. A safe surface interval of 15 minutes and use of the recompression-decompression schedules that were developed as a result of this experimentation are recommended for incorporation into the Project Tektite operational procedures.

## INTRODUCTION

Project Tektite, a joint research program presently being conducted by NASA, the U. S. Navy, the U. S. Department of the Interior, and the General Electric Corporation, will require that four scientist-aquanauts live for a period of 60 days in a habitat on the sea floor at a depth of 42 feet. The scientist will make frequent excursion dives from the habitat, both during the day and at night, in order to study the flora and the fauna of nearby coral reefs. The excursion dives will be made with standard scuba equipment, and two 71 cu. ft. scuba bottles will provide the air supply. This supply of air will permit the scientists to swim for about one to two hours at this depth, or to travel about 1000 feet from the habitat before returning to it.

The possibility that equipment failure, injury, or shark attack might force the swimmers to surface must be anticipated. Since their bodies will be saturated with the inert gas of their breathing mixture (91% nitrogen-9% oxygen) at the habitat pressure of 42 feet of seawater (FSW), ascent to the surface would constitute an emergency situation requiring immediate pressurization.

To what degree of safety a diver, breathing air at a depth greater than 33 feet (1 atm.) of seawater, could make a "no-decompression" ascent to surface when his slowest tissues are totally nitrogen saturated had never been established. Furthermore, the length of time that a diver can remain at surface pressure following such an ascent before experiencing the serious effects of decompression

sickness had never been determined, and this exposure time is critical to the safety of the Tektite divers. There are no valid decompression tables indicating the appropriate procedures to be followed in decompressing a diver from a state of total nitrogen saturation. Neither are there any published tables indicating the appropriate recompression and decompression procedures to be followed in the event of emergency surfacing in the circumstances under which the Tektite divers will be living and working.

#### PURPOSE

The present experimentation was conducted for two purposes: (1) to determine the maximum safe surface interval that the Tektite divers can sustain without developing symptoms of decompression sickness after remaining at a seawater depth of 42 feet in a habitat in which they are totally saturated with their breathing mixture, 160 mm. Hg. O<sub>2</sub> in nitrogen; and (2) to determine safe recompression-decompression schedules that will permit the Tektite divers to return to their habitat after this maximum safe surface interval, or that will allow their being brought to surface for emergency treatment, if such becomes necessary.

#### METHOD

Six tests were performed involving two subjects each. All of the subjects were divers whose ages varied from 20 to 52 years. The subjects were pressurized in a double-lock pressure chamber that was four feet in diameter and 14 feet long, in accordance with the compression-decompression schedules described hereafter. The

smallness of the chamber limited the movements of the subjects; they were, however, instructed to engage in mild physical activity for 15 minutes prior to any scheduled reduction in pressure.

The carbon-dioxide partial pressure in the chamber atmosphere was maintained between 0.6 and 5 mm. Hg. during periods of intermittent ventilation, with air, and at less than 4 mm. Hg. during continuous ventilation. In addition, the pressure chamber's carbon-dioxide content was reduced through a more rapid ventilation with air to an even lower level prior to any reduction in pressure. In each test, accuracy was held to less than a half foot of the prescribed simulated depth. The 91% nitrogen-9% oxygen gas mixture used in the final two hours of compression at the 42-foot level was purchased from commercial suppliers, and was tested to assure that accuracy was maintained to within 0.1% of the prescribed ratio.

After a change in the partial pressure of nitrogen in a breathing mixture, the change in nitrogen saturation of bodily tissues occurs at an exponential rate that is limited by the slowest tissue's half-saturation time. This half-saturation time, of course, varies greatly among individuals, but the time selected--360 minutes--is widely accepted in diving practices as accommodating the slowest tissues of the vast majority of the diving population.

Three days at 42 FSW would be required to bring the 360-minute tissues to an almost total state of nitrogen equilibrium with the proposed breathing atmosphere of the Tektite habitat. Because of the cost of doing so and the discomfort that the divers would have to



endure, it is impractical to saturate the Tektite divers for such a length of time in a chamber on a breathing mixture of 91%  $N_2$ -9%  $O_2$ . A shortened exposure period at greater depth, based upon the following theoretical considerations, was therefore calculated: Breathing air at a pressure of 1 atmosphere (which equals 33 FSW absolute) produces a partial pressure of nitrogen in the tissues equal to that of 26 FSW (absolute) pressure--i.e., 79% of the total pressure of 1 atmosphere.

The Project Tektite breathing atmosphere will be a mixture of oxygen and nitrogen, the oxygen to be limited to 7 FSW (160 mm. Hg.) partial pressure and the nitrogen to a partial pressure of 68 FSW. (The gauge pressure of 42 FSW is equal to 75 FSW absolute pressure, i.e., 42 FSW + 33 FSW [1 atm.] equals 75 FSW absolute.) The Tektite divers will therefore undergo an increase in nitrogen partial pressure upon changing from breathing air on the surface to breathing the atmosphere in the Tektite habitat--i.e., a pressure of 42 FSW (68 FSW - 26 FSW = 42 FSW).

If the 42-FSW increase in nitrogen partial pressure in the Tektite breathing atmosphere were doubled, the nitrogen partial pressure in the slowest half-saturation time tissue would, theoretically, be increased to 50% of the 84-FSW change in the atmospheric nitrogen partial pressure during the period that the slowest tissues half saturate, namely, 360 minutes. Under a pressure of 139 FSW absolute (106 FSW gauge pressure), air has a nitrogen partial pressure of 110 FSW. The nitrogen pressure at 110 FSW is 84 FSW over that of air at surface pressure (1 atm.); it is twice the difference between the nitrogen

partial pressure of air at 1 atm. and that of the atmosphere planned for the Tektite habitat. In six hours, therefore, it is theoretically possible to bring about total equilibrium between the nitrogen partial pressure in the slowest tissues and that of the Tektite breathing atmosphere that would be approximated by a diver's breathing the Tektite atmosphere for three days (or more) at 42 FSW.

The tissues with a one-half saturation time of less than 360 minutes will attain higher levels of nitrogen tissue tension during the 360-minute pressurization at 106 FSW, but will eliminate nitrogen more rapidly when the pressure is decreased. In the present experimentation, it was necessary that the nitrogen partial pressure of all the tissues be approximately equal to that in the Tektite atmosphere (i.e., 68 FSW); chamber pressure was therefore decreased from 106 FSW to 53 FSW gauge after 360 minutes in order to desaturate the faster half-saturation time tissues. Breathing air at 53 feet produces the same nitrogen partial pressure in the tissues as is produced by breathing a 91%  $N_2$ -9%  $O_2$  mixture at a depth of 42 feet. The nitrogen partial pressure is equal to the gauge depth in the breathing mixture plus the equivalent absolute depth at sea level (33 feet) multiplied by the percentage of nitrogen in the mixture. In the Tektite atmosphere, the equation is as follows:  $42 \text{ FSW} + 33 \text{ FSW} \times .91 N_2 = 68 \text{ FSW}$ . Breathing air at 53 feet nitrogen partial pressure is:  $53 \text{ FSW} + 33 \text{ FSW} \times .79 N_2 = 68 \text{ FSW}$ . As far as the nitrogen partial pressure is concerned, therefore, both conditions are equal.

Calculations indicate that 16 hours at 53 FSW pressure are required so that the tissues with shorter half-saturation times desaturate to approximate the Tektite tissue nitrogen partial pressure. Some of the slower tissues will have nitrogen partial pressures slightly in excess of the Tektite habitat's nitrogen content at the end of this time. To prevent any possible contributory effects resulting from the increased partial pressure of oxygen, the final two hours prior to testing the surface interval were spent at 42 FSW, during which time the subjects breathed the specified mixture of 91%  $N_2$ -9%  $O_2$ .

The following schedule of pressure exposure was utilized to establish total equilibrium between the nitrogen saturation in the bodily tissues having a half saturation time of 360 minutes and the nitrogen content of the Project Tektite breathing atmosphere:

1. Breathing air at 106 FSW for six hours.
2. Breathing air at 53 FSW for 16 or 35 hours.
3. Breathing a 91% nitrogen-9% oxygen mixture at 42 FSW for two hours.

The first three tests utilized a minimum desaturation period only 16 hours. This period was increased to 35 hours in the last three tests to determine the validity of the shorter desaturation interval. The allowable safe surface interval following the above schedule was determined by decompressing the subjects from 42 FSW to surface pressure in one minute, and then observing them for periods lasting 10, 15, and 20 minutes.

Following the interval at surface pressure, the subjects were recompressed in accordance with the schedule in Table I. These decompression schedules were calculated so that the Tektite scientists can be safely recompressed and decompressed to habitat depth after any emergency exposure that they might be forced to undergo.

Table I  
SURFACE DECOMPRESSION  
TREATMENT SCHEDULES FOR RETURN TO HABITAT

Schedule	Surface Interval (Min.)	Decompression Stages					Total Time
		60 ft.	55 ft.	50 ft.	45 ft.	40 ft.	
A	0-10		20 min. (O <sub>2</sub> )	20 min. (air)	20 min. (O <sub>2</sub> )		60 min.
B	10-20	20 min. (O <sub>2</sub> )	20 min. (air)	20 min. (O <sub>2</sub> )	20 min. (air)	20 min. (O <sub>2</sub> )	100 min.

Safe decompression schedules are also needed so that the scientists can be further decompressed from the habitat depth to surface should emergency medical treatment be required. Two decompression procedures were therefore tested, one utilizing air breathing only, and the other utilizing alternate periods of air and oxygen breathing (see Table II). Four subjects were decompressed according to the air table, and six according to the air-oxygen schedule. A typical dive profile is shown in Figure 1.

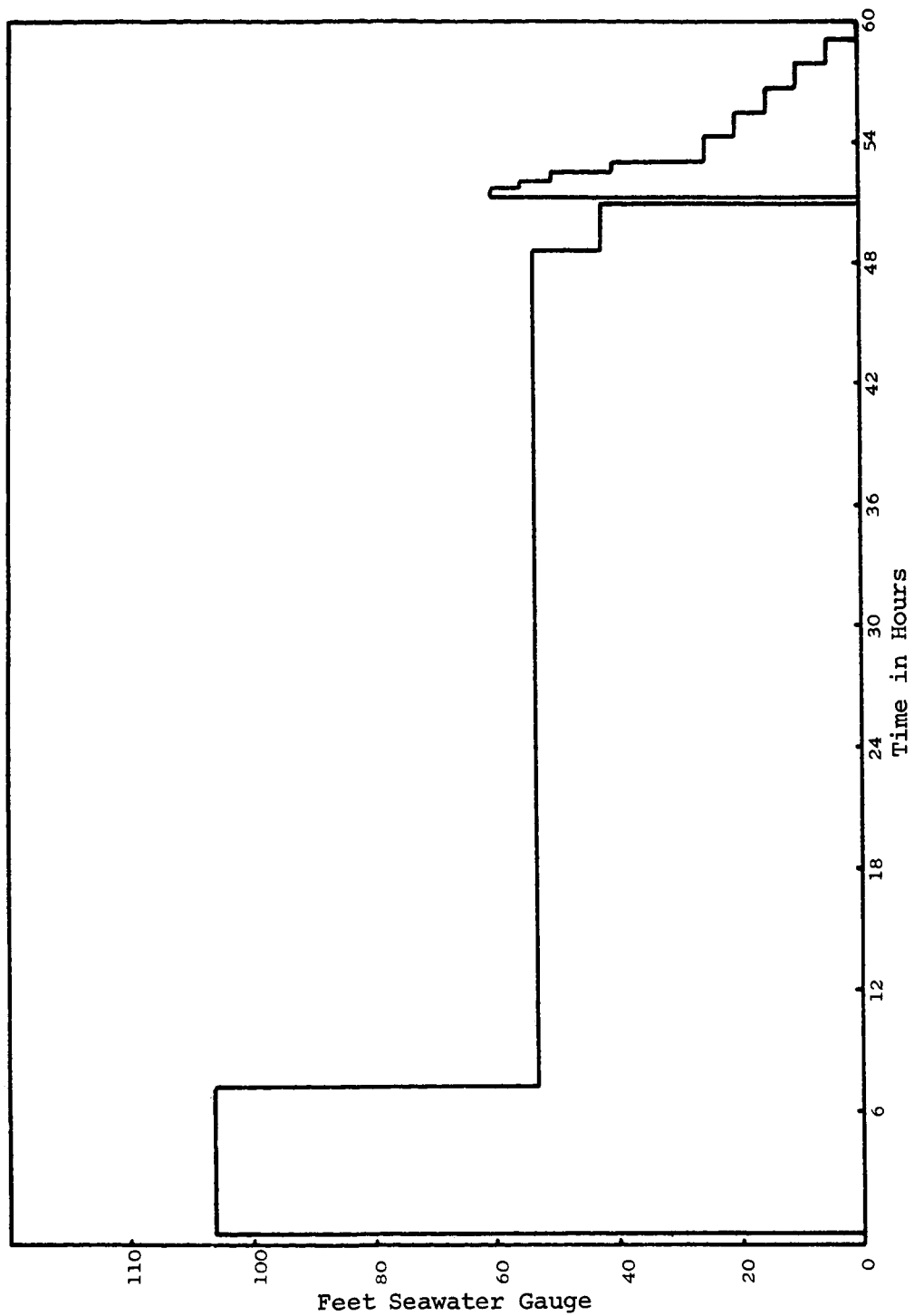


Figure 1. Test profile for Tektite I with approximately 35 hours at 53 feet.

Table II

DECOMPRESSION SCHEDULES FOR  
RETURN TO SURFACE AFTER USE OF TABLE I

Schedule	Decompression Stages					Total Time
	25 ft.	20 ft.	15 ft.	10 ft.	5 ft.	
Air decompression		2 hrs.	2 hrs.	2 hrs.	3 hrs.	9 hrs.
Air-oxygen decompression	1 hr. (O <sub>2</sub> )	1 hr. (air)	1 hr. (O <sub>2</sub> )	1 hr. (air)	1 hr. (O <sub>2</sub> )	5 hrs.

The two decompression schedules that were utilized in these tests are shown in Figure 2.

An additional test, involving two Navy subjects, was carried out to compare the efficacy of the emergency decompression schedules proposed herein with that of the decompression schedule adopted by the U. S. Navy for use in the Tektite Program (see Figure 3 and Appendix A).

### RESULTS

A schedule of the test procedures is shown in Table III (page 12). One of the two subjects exposed to the 10-minute simulated surface interval noticed a very mild pain (grade 1) in his right shoulder. Complete relief was obtained upon recompression to a simulated depth of 55 FSW. The other subject remained symptom-free. There were no symptoms reported by the six subjects who were exposed to the 15-minute surface interval.

Of the two subjects exposed to the 20-minute surface interval, one subject remained symptom-free. The other subject experienced marked

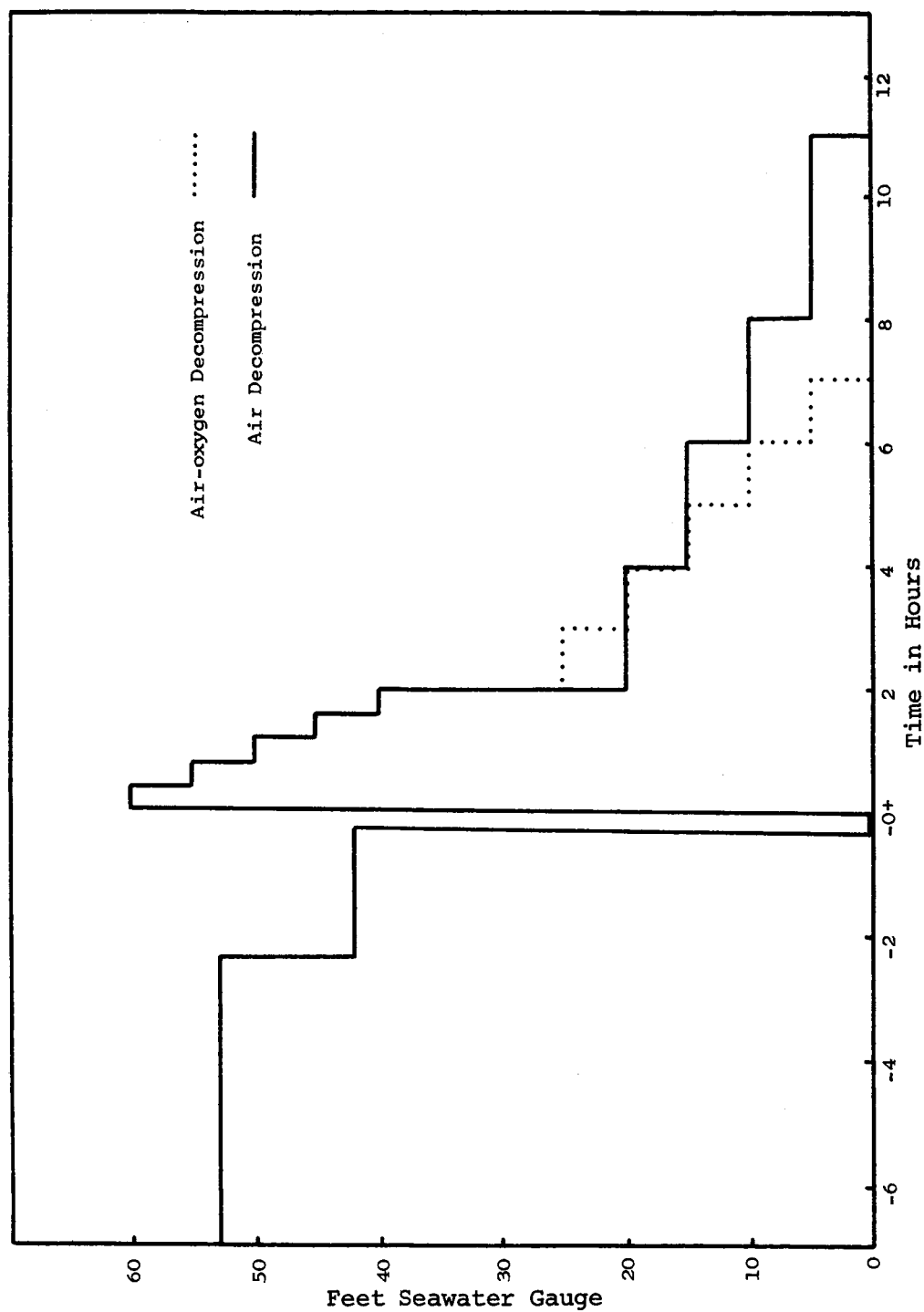


Figure 2. Treatment and decompression schedules after surfacing from total saturation at 42 FSW.

Table III

## TEST PROFILES

Test #	Time at 106 Feet on Air	Time at 53 Feet on Air	Time at 42 Feet on 91%N <sub>2</sub> -9%O <sub>2</sub>	Surface Interval in Minutes	Treatment Schedule	Individual Decompression Schedules
1	6 hrs.	16 hrs., 5 min.	1 hr., 48 min.	10	A	One diver on air, one diver on air-oxygen
2	6 hrs.	15 hrs., 55 min.	2 hrs.	20	B	One diver on air, one diver on air-oxygen
3	6 hrs.	35 hrs., 25 min.	2 hrs.	15	B	Both divers on air
4	6 hrs.	34 hrs., 25 min.	2 hrs.	15	B	Both divers on air-oxygen
5	6 hrs.	35 hrs., 24 min.	2 hrs.	15	B	Both divers on air-oxygen
6	6 hrs.	35 hrs., 23 min.	2 hrs.	None		Decompressed on schedule in Appendix A

Compression to 106 feet: 2 minutes  
 Ascent from 106 feet to 53 feet: 5 minutes  
 Ascent from 53 feet to 42 feet: 2 minutes  
 Ascent from 42 feet to surface: 2 minutes



neurocirculatory symptoms in the 19th minute of his surface interval. He was immediately recompressed and reported complete relief of symptoms upon arrival at a recompression depth of 60 feet.

Two U. S. Navy volunteer subjects, both qualified divers, were compressed in accordance with the previously tested nitrogen saturation schedule, and were then decompressed on the prolonged air-oxygen schedule (see Figure 3 and Appendix A). One of the two subjects suffered grade 1 bends in the right ankle upon surfacing. The symptom disappeared without treatment after four hours of breathing air at surface pressure.

The tables used to recompress the subjects from surface pressure to 55 or 60 FSW, and then to decompress them to the simulated habitat pressure (42 FSW), were apparently safe and effective in the treatment of the two cases (out of 10 subjects) of decompression sickness that occurred during the surface interval. No incidence of decompression sickness occurred during the phase in which the subjects were returned to simulated habitat pressure.

None of the four subjects who were decompressed from 42 FSW on the air decompression table (see Table II) experienced decompression sickness. However, of the six subjects decompressed from 42 FSW on the air-oxygen decompression schedule, one subject suffered very mild (grade 1) bends pain in his right ankle upon surfacing. This symptom persisted and eventually involved the subject's right knee as well, requiring compression to 60 feet and treatment according to a modification of Table 6 of the U. S. Navy Diving Manual (see Figure 4).

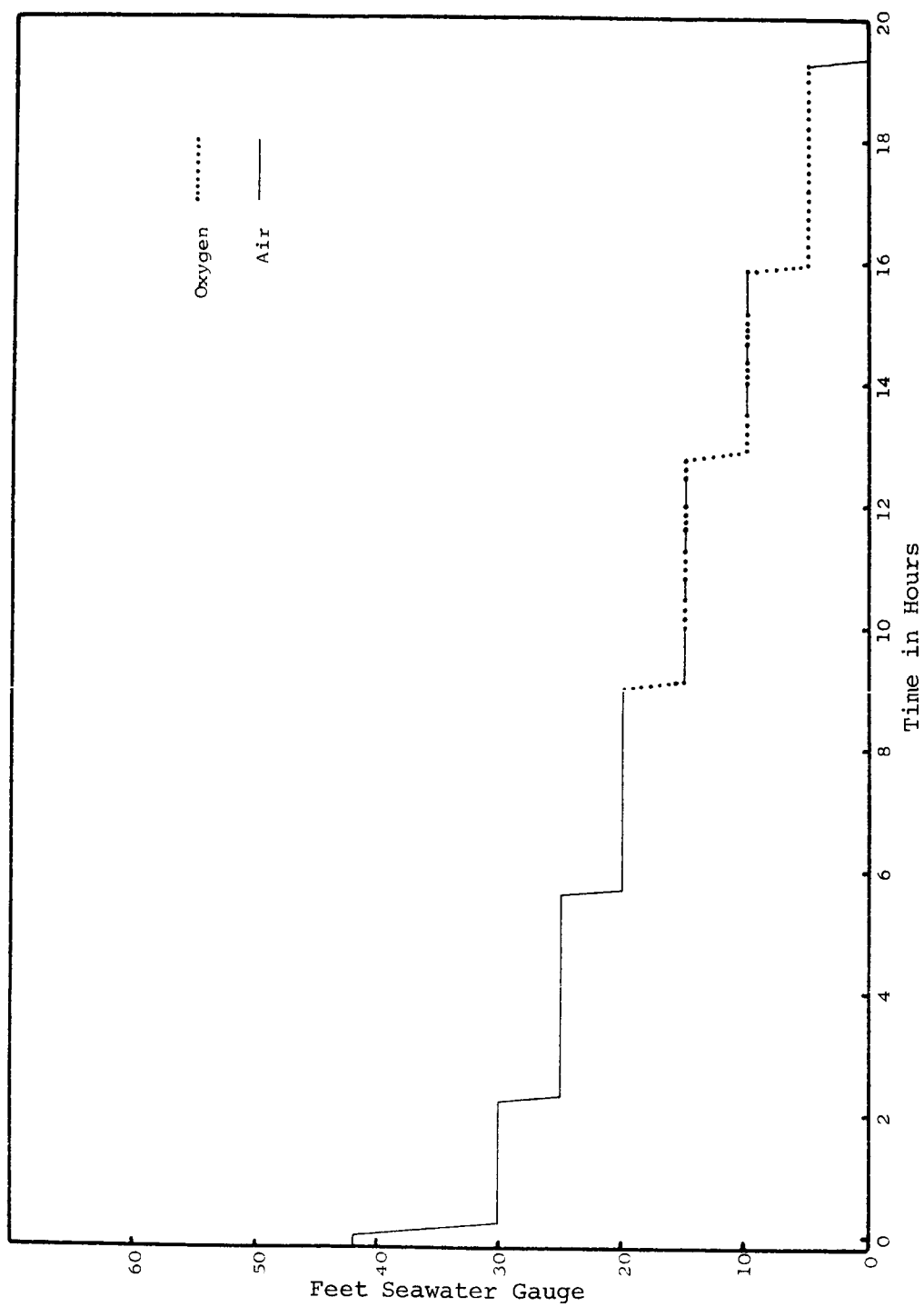


Figure 3. Regular decompression schedule for Tektite I.

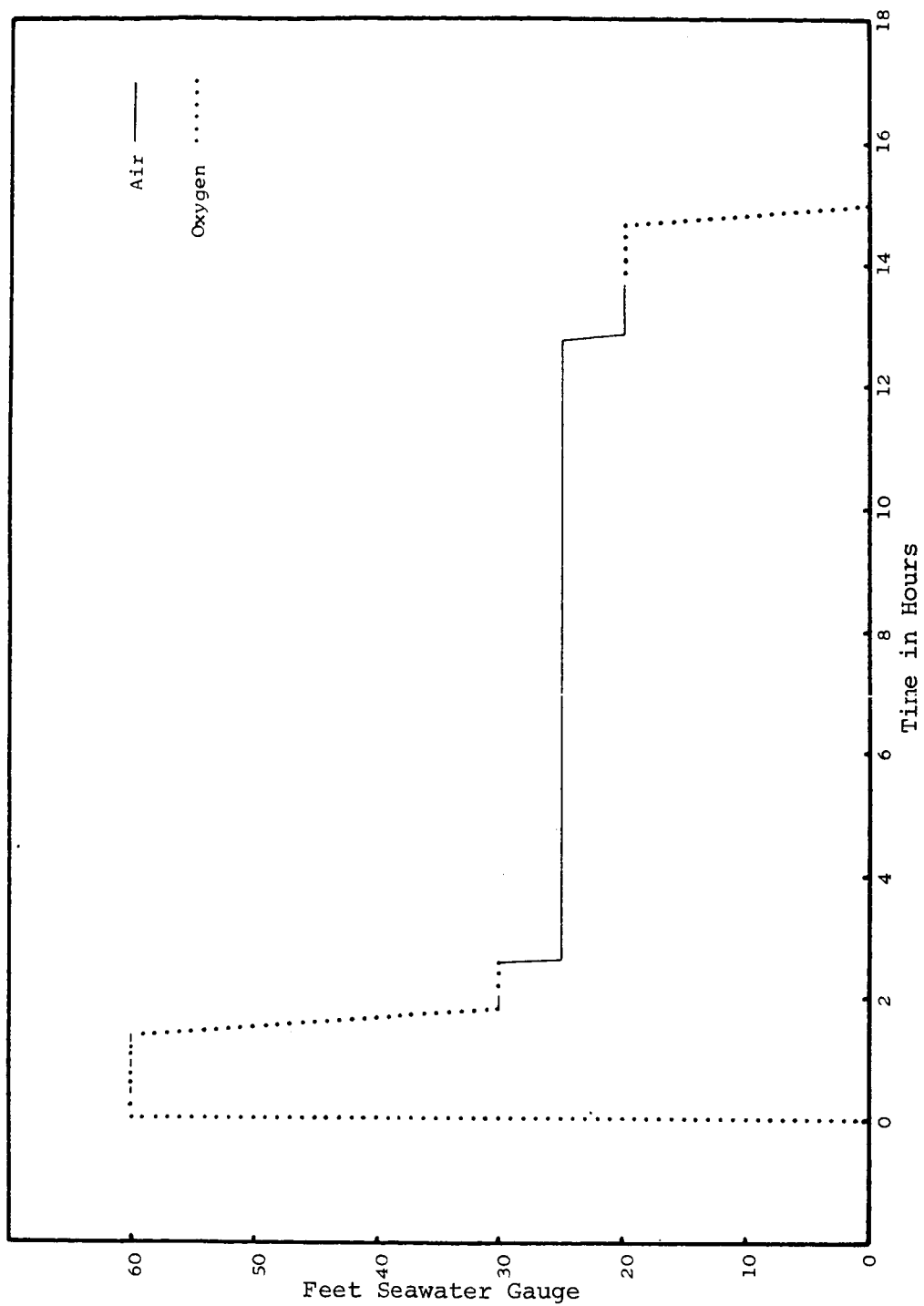


Figure 4. Treatment for decompression sickness resulting from test #5.

This subject has a history, it should be noted, of an old injury to the ankle, and suffered similar bends symptoms when he was decompressed according to the standard Project Tektite decompression schedule (see Test #6, Table III). He had also suffered previous attacks of bends in this ankle. Shortly after his arrival at 30 feet, the subject complained of "soreness in his chest" and mild substernal distress when he breathed, which were interpreted as being caused by oxygen toxicity. He was then brought to 25 feet and remained at that pressure breathing air overnight, or 10 hours. In the morning he was brought to 20 feet, where he remained for 50 minutes breathing air. He was given oxygen for 60 minutes at the 20-foot depth, and remained on oxygen during his 20-minute ascent to surface.

#### DISCUSSION

The test results indicate that after total saturation at 42 FSW with the proposed Tektite breathing mixture of 91%  $N_2$ -9%  $O_2$ , a surface interval lasting no longer than 15 minutes is reasonably safe against an attack of decompression sickness. One subject in the present investigation experienced serious symptoms of decompression sickness 19 minutes after being brought to surface following the experimental saturation exposure. His symptoms might well have proved fatal had not immediate recompression been possible. A 20-minute surface interval therefore appears to be unsafe. The possibility that decompression sickness will occur in some subjects during a 15-minute surface interval following saturation with the Tektite Habitat atmosphere cannot be ruled out, since only six tests were made in the

present experimentation utilizing the same decompression schedules as will be used in Project Tektite.

Although symptoms did not manifest themselves in the other subjects who were exposed to the 15- and 20-minute intervals, there was undoubtedly bubble formation in their tissues which, had the surface interval been extended, would eventually have caused decompression sickness. When tissues are supersaturated with inert gas, the stage is set for an attack of decompression sickness should any further reduction in pressure occur. If supersaturation is great enough, the solution of the gas in the tissues becomes unstable, resulting in a separation into gas and liquid phases. The bubbles thus formed continue to grow and create sufficient pressure to cause tissue damage or symptoms of decompression sickness, or both.

Once a critical reduction in ambient pressure has taken place, it is only a matter of time before symptoms of decompression sickness become manifest. It must therefore be assumed that some degree of bubble growth will occur during the surface interval following any emergency ascent from the Tektite habitat, whether or not the subject experiences any symptoms of it. The air-oxygen treatment tables shown in Table I, page 8, were calculated to dissolve this bubble formation during decompression to habitat pressure.

By means of a further pressure reduction, according to the schedule shown in Figure 3, page 14, from the equivalent of habitat to surface pressure, the effectiveness of the treatment schedule outlined in Table II, page 10, was tested. Any nitrogen bubbles that form

during a surface interval, even symptomatic ones, that are not dissolved through treatment can be expected to become aggravated by further pressure reduction. During decompression or following a diver's return to sea-level pressure, symptoms of previous silent bubble formation may become evident, or symptoms that had disappeared may reassert themselves.

One case of decompression sickness occurred during testing of the proposed standard decompression schedule, and one also during the testing of the proposed emergency decompression schedule for Tektite I. As previously noted, both instances involved the same individual, who is believed to be unusually susceptible to decompression sickness in this type of pressure exposure. All the other test subjects were able to tolerate the programmed decompression schedules without difficulty.

It is interesting to note that decompression time can be sharply reduced in emergency decompression schedules through the subjects' breathing air and oxygen alternatively. When air alone was breathed in the present experimentation, a decompression time of nine hours was required, whereas the interval was reduced to five hours when pure oxygen and air were breathed intermittently (see Table II). The effectiveness of denitrogenization via oxygen breathing in Tektite emergency procedures is obvious.

In tests requiring near-total saturation of the tissues with nitrogen, a major difficulty lies in the prolonged period of time required

to achieve that saturation level. Because of the exponential rate at which nitrogen is absorbed and discharged by bodily tissues, the process of attaining a condition of complete equilibrium between the inert gas in the inspired breathing medium and in the bodily tissues is never completed with pressure exposure at a single level. In Tektite experimentation, the required level of nitrogen partial pressure in the bodily tissues is 68 FSW (absolute). After a diver has remained three days at 42 FSW breathing the Tektite atmosphere, his slowest half-time tissue (360 minutes) will theoretically attain a nitrogen partial pressure of 67 to 68 FSW (absolute).

The method used in the present investigation to produce maximum nitrogen partial pressure in the slowest tissue--i.e., doubling the nitrogen partial gradient of the breathing atmosphere--was apparently effective. After a diver spends 16 hours breathing air at 53 FSW, his slower tissues--those having a faster half-saturation time than the 360-minute tissues do--had a nitrogen partial pressure of 68 to 69 FSW. This small excess in nitrogen partial pressure over the Tektite nitrogen pressure would have, at most, a very slight effect on the required Tektite decompression, and if anything would impose a slightly more rigid test of the decompression table to be followed.

There was no significant difference between the test results involving 16 hours of desaturation at 53 FSW and those involving 35 hours of desaturation at 53 FSW. Extending the period of time spent at 53 FSW from 16 to 35 hours reduces the nitrogen partial pressure

in the slower tissues so negligibly that the extension of time beyond 16 hours cannot be considered significant in the results of any decompression schedule used.

### CONCLUSIONS AND RECOMMENDATIONS

1. In the event that Project Tektite aquanauts make a planned or accidental ascent to surface after maximum nitrogen saturation at 42 FSW, a surface interval not to exceed 15 minutes is considered safe. This surface interval is recommended for use in formulating Project Tektite emergency procedures.
2. The emergency recompression and decompression schedules shown in Tables I and II were proven effective, and are suggested for use in treatment of Tektite aquanauts after emergency surfacing. It is also recommended that these schedules be utilized to return Tektite divers to their habitat or to the surface under nonemergency circumstances.
3. The decompression schedule formulated for the standard (as opposed to emergency) decompression of Project Tektite divers at the end of their 60-day submergence was found to be satisfactory. Its use is therefore recommended.
4. Doubling the nitrogen partial pressure gradient for a period of time equal to that of the half-saturation time of the slowest tissue demonstrated empirically that a desired tissue tension can be reached by the end of that time period. The use



of this technique is recommended in experimentation involving total saturation of the tissues with nitrogen or other inert gases.

5. The effectiveness of the schedules for treatment (Table I) and decompression (Table II) that were developed and tested under this contract was in part dependent upon adherence to the established CO<sub>2</sub> partial-pressure limits set. Effectiveness likewise depended upon the subjects' doing mild exercise prior to each decompression phase, and also upon their not deviating more than a half foot from the prescribed pressure at any time.
6. The decompression schedule set out in Appendix A was tested under the same conditions as those in Tables I and II. Its successful use is also dependent upon the divers' following the decompression procedures detailed in it, never deviating more than a half foot from the prescribed pressure. Its successful use is furthermore dependent upon the divers' staying within the CO<sub>2</sub> partial-pressure limits, as well as their doing mild exercise during decompression.

## Appendix

### REGULAR DECOMPRESSION SCHEDULE FOR TEKTITE I

1. Aquanauts will be transferred via the Personnel Transfer Capsule to the Deck Decompression Chamber and held at a depth of 42 feet until all are transferred and topside crew is ready for decompression.
2. All depth changes during the decompression will be made at a rate of 1 foot per minute. In the event the depth changes occur slower the time will be added onto total decompression.

Depth	Time at Stop (Minutes)	Total Decompression Time (Minutes)	Breathing Media
42 ft.			
↓	12	12	Air
30	120	132	Air
↓	5	137	Air
25	200	337	Air
↓	5	342	Air
20	170	512	Air
20	30	542	Oxygen
↓	5	547	Oxygen
15	20	567	Air
15	30	597	Oxygen
15	20	617	Air
15	30	647	Oxygen
15	20	667	Air
15	30	697	Oxygen
15	20	717	Air
15	30	747	Oxygen
↓	5	752	Oxygen
10	60	812	Air
10	30	842	Oxygen
10	20	862	Air
10	30	892	Oxygen
10	20	912	Air
10	40	952	Oxygen
↓	5	957	Oxygen
5	200	1157	Air
↓	5	1162	Air
Surface			

Total decompression time is 1162 minutes or 19 hours, 22 minutes.

Total oxygen decompression time is 265 minutes or 4 hours, 25 minutes.